Technique for Direct eV-Scale Measurements of the Mu and Tau Neutrino Masses Using Supernova Neutrinos

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Early black hole formation in a core-collapse supernova will abruptly truncate the neutrino fluxes. The sharp cutoff can be used to make model-independent time-of-flight neutrino mass tests. Assuming a neutrino luminosity of 10^{52} erg/s per flavor at cutoff and a distance of 10 kpc, SuperKamiokande can detect an electron neutrino mass as small as 1.8 eV, and the proposed OMNIS detector can detect mu and tau neutrino masses as small as 6 eV. This *Letter* presents the first technique with direct sensitivity to eV-scale mu and tau neutrino masses.

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Introduction: Despite decades of experimental effort, the values of the neutrino masses remain elusive. While the laboratory bound on the electron neutrino mass is about 3 eV [1], the laboratory bounds on the mu and tau neutrino masses are much weaker: 170 keV [2] and 18 MeV [3], respectively. Only recently have neutrino oscillation experiments found strong evidence for nonzero *differences* of squared neutrino masses. Once discovered, the values of the neutrino masses may provide important clues to physics beyond the Standard Model. In some scenarios, e.g., with the see-saw mechanism [4], the mu and tau neutrino masses are expected to be much larger than the electron neutrino mass. If they are at the eV scale or greater, the neutrino masses could also be important cosmologically as a component of the long-sought dark matter. It is therefore crucial to devise direct tests of the mu and tau neutrino masses with sensitivity reaching the eV scale. While neutrino mass tests based on cosmological considerations may reach the eV scale, they are indirect (no neutrinos are detected) and depend upon the other cosmological parameters being independently known [5].

The best known possibility for directly measuring the mu and tau neutrino masses is by time-of-flight measurements of supernova neutrinos, comparing the arrival time of the mu and tau neutrinos to that of the electron neutrinos. However, this is complicated by the long intrinsic duration ($\simeq 10$ s) of the neutrino signal and the fact that its detailed characteristics are model-dependent. Beacom and Vogel have shown that a technique based on the average arrival times $\langle t \rangle$ is model-independent and is sensitive to delays as small as $\simeq 0.1$ s [6]. This would allow detection of mu or tau neutrino masses down to 45 eV in SuperKamiokande (SK) and 30 eV in the Sudbury Neutrino Observatory (SNO). If the mu and tau neutrino masses (strictly speaking, those of the relevant mass eigenstates) are nearly degenerate, as suggested by the atmospheric neutrino results [7], then the sensitivity would improve by about $\sqrt{2}$. Unfortunately, it seems difficult to improve the results with this technique, since the mass sensitivity scales with the detector mass M_D as $1/M_D^{1/4}$ [6]. To reach the few-eV scale would require detectors 10^4 times larger, which seems impossible.

In this *Letter*, we discuss a new time-of-flight technique for measuring neutrino masses that *can* reach the eV scale. This technique is applicable if the proto-neutron star forms a black hole early enough to abruptly terminate the neutrino signal. We state only our most important results; the details will be discussed at length in a forthcoming paper [8].

Expected Neutrino Signal: We consider black hole formation which occurs soon (~ 1 s) after core collapse (other scenarios are considered in Ref. [8]). Black hole formation is triggered by accretion, which drives the proto-neutron star mass above the maximum stable neutron star mass. The neutrino signal expected in this scenario has been studied by Burrows [9] and Mezzacappa and Bruenn [10]. In these models, the neutrino luminosities were fairly constant at more than 10^{52} erg/s per flavor until abruptly terminated by black hole formation. In fact, the transition should have a nonzero duration, of order the light crossing time $2R/c \simeq 0.1$ ms, as the proto-neutron star radius shrinks to that of the final black hole. During the transition, the gravitational redshift, originally $\simeq 10\%$, rapidly diverges, truncating the neutrino signal. Using a singularity-avoiding code, Baumgarte et al. [11] studied the transition and found its duration to be 0.5 ms. Thus, we can consider the neutrino fluxes to be sharply and simultaneously terminated.

The results below assume a luminosity $L_{BH} = 10^{52}$ erg/s per flavor at the cutoff time t_{BH}, and a distance

$D = 10$ kpc. We assume the following temperatures: $T = 3.5$ MeV for ν_e, $T = 5$ MeV for $\bar{\nu}_e$, and $T = 8$ MeV for ν_μ, ν_τ, $\bar{\nu}_\mu$, and $\bar{\nu}_\tau$. It will be shown that the necessary quantities can be *measured* in a realistic situation.

Neutrino Mass Effects: At lowest order, a neutrino with mass m (in eV) and energy E (in MeV) will have an energy-dependent delay (in s) relative to a massless neutrino in traveling over a distance D (in 10 kpc):

$$\Delta t(E) = 0.515 \left(\frac{m}{E}\right)^2 D\,. \tag{1}$$

The distance is scaled by the approximate distance to the Galactic center, though a supernova may be detected from anywhere in the Galaxy. For the smallest detectable masses, the delay effects will be visible only after the sharp cutoff, where no events are otherwise expected. Since the delays are very small, the luminosities and temperatures can be taken as constant over the short interval before t_{BH}. The event rate for $t > t_{BH}$ is [8]:

$$\frac{dN}{dt}(t) = C \left[\frac{L_{BH}}{10^{51}\mathrm{erg/s}}\right] \int_0^{E_{max}} dE\, f(E) \left[\frac{\sigma(E)}{10^{-42}\mathrm{cm}^2}\right], \tag{2}$$

where $f(E)$ is the neutrino energy spectrum and $\sigma(E)$ the cross section. The upper limit E_{max} on the integral allows only delays as large as $t - t_{BH}$, i.e.,

$$E_{max} = m\sqrt{\frac{0.515D}{t - t_{BH}}}\,, \tag{3}$$

where the units are as in Eq. (1). Note that the time and neutrino mass dependence appear only through E_{max}. For $t < t_{BH}$, $E_{max} \to \infty$, and the rate is constant. If the neutrino energy can be measured, as for some charged-current reactions, then the event rates for different neutrino energies can easily be obtained. For an H_2O detector, the constant C is

$$C_{\mathrm{H2O}} = (1.74/\mathrm{s}) \left[\frac{M_D}{1\ \mathrm{kton}}\right] \left[\frac{10\ \mathrm{kpc}}{D}\right]^2 \left[\frac{1\ \mathrm{MeV}}{\langle E\rangle}\right]. \tag{4}$$

For a Fermi-Dirac spectrum, $\langle E\rangle = 3.15T$. The constant for a ^{208}Pb detector can be obtained by scaling by the relative number of targets/kton, i.e., 18/208.

The expected number of delayed counts after t_{BH} can be calculated using Eq. (2). This will be useful when t_{BH} can be measured independently. It can be shown [8] that this has the very simple form:

$$N_{del} = \frac{dN}{dt}(t_{BH}) \times 0.515 \left(\frac{m}{E_c}\right)^2 D\,, \tag{5}$$

where the event rate is in s^{-1}, and the other units are as in Eq. (1). This formula would obviously be true if only a single energy contributed and the sharp cutoff in the event rate were rigidly translated by the delay. But it is remarkable and very convenient that it is still true even when there is a spectrum of energies and the event rate develops a decaying tail past the cutoff (as in Figs. 1 and 2). The physical significance of the "central" energy E_c is that it is (to an excellent approximation) simply the Gamow peak of the falling thermal spectrum and the rising cross section. As derived, this is an exact result.

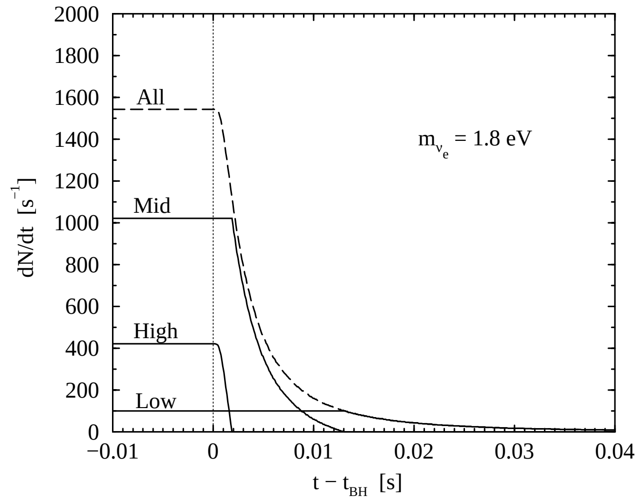

FIG. 1. The event rates due to $\bar{\nu}_e + p \to e^+ + n$ in SK, for different ranges of the neutrino energy: "Low" ($0 \le E \le 11.3$ MeV, contains 2.4 events past the true t_{BH}), "Mid" ($11.3 \le E \le 30$ MeV, 4.8 events), "High" ($30 \le E \le \infty$ MeV, 0.5 events), and "All" (all energies, 7.7 events). Note that only the rate after about t_{BH} is shown, and that the range of $t - t_{BH}$ is very short.

Electron Neutrino Mass: We first consider the measurement of t_{BH} and m_{ν_e} using the $\bar{\nu}_e + p \to e^+ + n$ events in the 32-kton SK detector. For $T = 5$ MeV, the thermally-averaged cross section (for the *sum* of the two protons in H_2O) is $44. \times 10^{-42}$ cm^2 [12]. The event rate at or before t_{BH} is thus $\simeq 1500$ s^{-1}. After t_{BH}, the rate is zero if $m_{\nu_e} = 0$ and will develop a tail if $m_{\nu_e} > 0$.

For a sharp edge, the edge position can be determined with an error given by the reciprocal of the event rate before the edge, i.e., the event spacing [8,13]. If we knew that $m_{\nu_e} = 0$, then t_{BH} would be determined to $\simeq 1$ ms. More realistically, a mass as large as the laboratory bound, $m_{\nu_e} \lesssim 3$ eV [1], would cause delays as large as 40 ms, so that the extracted t_{BH} would be too large.

However, we can simultaneously measure m_{ν_e} and t_{BH} by splitting the $\bar{\nu}_e + p \to e^+ + n$ data into different ranges of neutrino energy (using $E_\nu \simeq E_e + 1.3$ MeV). These are defined in the caption of Fig. 1. The Low group must be excluded from consideration because these events have positron total energy less than 10 MeV, and can be confused with the 5 − 10 MeV gammas from neutral-current reactions on ^{16}O [14]. The High group has very little delay and will thus primarily be sensitive to t_{BH}. Then the Mid group will determine m_{ν_e}, by counting events

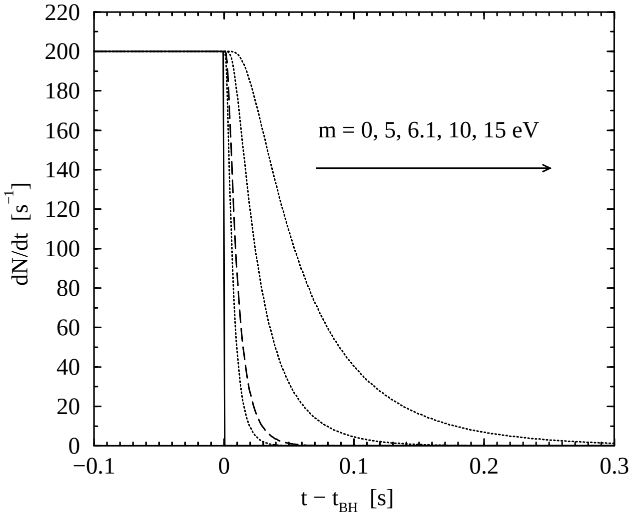

FIG. 2. The results for the combined 1-n neutral-current event rate due to ν_μ, ν_τ, $\bar{\nu}_\mu$, and $\bar{\nu}_\tau$ in OMNIS. Note that only the rate after about t_{BH} is shown. Before t_{BH}, other reactions contribute about 20% of the total neutron rate; they are not included here, and will have to be statistically subtracted from the measured rate. The mu and tau neutrino masses are assumed degenerate [7]. The $m = 0$ case is drawn with a solid line. The $m = 6.1$ eV case, with 2.3 events expected in the tail, is the first case that can be reliably distinguishable from $m = 0$, and is drawn with a long-dashed line. The results for other masses are drawn with dotted lines.

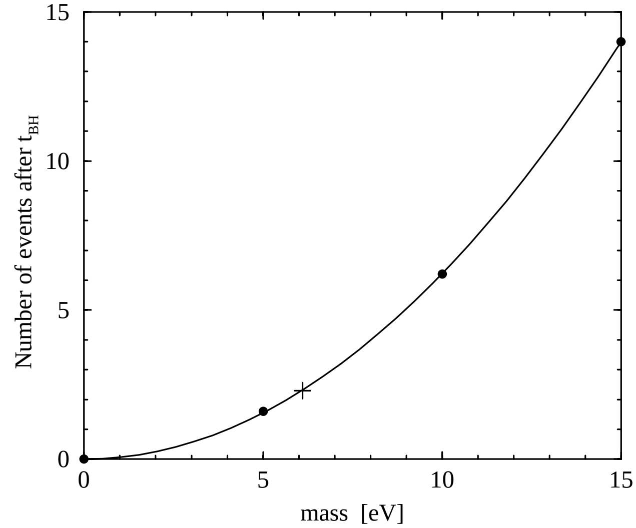

FIG. 3. The expected number of delayed counts N_{del} in OMNIS as a function of the neutrino mass. The points are obtained by direct numerical integration of Eq. (2). The "+" indicates the smallest discernible mass at the 90% CL. The solid line is obtained with Eq. (5), using $E_c = 40.7$ MeV, the Gamow peak energy.

delayed past the t_{BH} determined by the High group.

In Fig. 1, we show a possible analysis for the case of $m_{\nu_e} = 1.8$ eV. In the High group, the number of events in the tail is $\lesssim 1$, so the cutoff appears sharp and is specified to within $\simeq 2$ ms. This uncertainty affects the expected number in the Mid group by $\simeq 2$ events. Even so, one can still reliably see a few delayed counts after the measured t_{BH}, enough to establish a nonzero mass (the statistics are discussed in more detail below). A more sophisticated fit would improve our results somewhat, and we assume a final uncertainty on t_{BH} of about 1 ms. For a supernova in which the neutrino fluxes are not truncated by black hole formation, SK could detect an electron neutrino mass as small as ~ 3 eV [15].

Mu and Tau Neutrino Masses: We consider mu and tau neutrino detection in OMNIS, a proposed supernova neutrino detector based on lead and iron [16]. Since their energies are below the charged-current thresholds, supernova mu and tau neutrinos can be detected only by their neutral-current interactions. On the other hand, due to the temperature hierarchy, they will dominate the neutral-current yields. In OMNIS, the dominant neutral-current reaction is the spallation of single neutrons from lead. The neutrons could be detected by capture in a gadolinium-doped liquid scintillator, which yields an 8-MeV gamma cascade in about 0.030 ms (much smaller than typical mass delays).

For $T = 8$ MeV, the thermally-averaged cross section for the *sum* of ν_μ and $\bar{\nu}_\mu$ (or ν_τ and $\bar{\nu}_\tau$) on ^{208}Pb, including the 1-neutron spallation probability, is 760×10^{-42} cm^2 [17]. The cross sections on ^{206}Pb and ^{207}Pb, which together comprise 46% of natural lead, are expected to be similar [8]. For a supernova at 10 kpc in which the neutrino fluxes are not cut off by black hole formation, we assume that OMNIS will have $\simeq 1000$ 1-neutron neutral-current events due to ν_μ, ν_τ, $\bar{\nu}_\mu$, and $\bar{\nu}_\tau$ on lead (the events on iron are not included in our calculations). This goal could be met with a 2.2 kton lead detector with perfect neutron detection efficiency. A realistic design based on 4 kton of lead and 10 kton of iron, and with about this many events, is described by Boyd [16].

In Fig. 2, we plot the relevant neutral-current rate for different values of the neutrino mass, calculated using Eq. (2). In Fig. 3, we plot the number of delayed events N_{del} as a function of the neutrino mass, using Eq. (5) and by direct integration. Equation (5) is remarkable for its simplicity, and also because it is written in terms of measurable quantities. The cutoff time t_{BH} will be measured in SK. The neutral-current event rate at or before t_{BH} will be measured in OMNIS, as will N_{del}. The central energy E_c depends on the mu and tau neutrino temperature, which can be estimated by the neutral-current yields on different targets [8]. We assume that the distance D can be determined by astronomical means.

Given the measured value of N_{del}, Eq. (5) can be immediately solved for the best-fit neutrino mass. If $N_{del} = 0$ is measured, then the best-fit mass is $m = 0$, and an upper limit can be placed. An expectation of 2.3 counts fluctuates down to 0 counts only 10% of the time. Thus, setting $N_{del} = 2.3$, an upper limit on the mass m_{lim} is obtained. This is the largest mass, given the expected Poisson statistics, that could be confused with the massless case. For the present case, this is 6.1 eV.

Since the fractional error on N_{del} due to Poisson statistics is large ($\simeq 1/\sqrt{2.3} \simeq 65\%$), errors on other inputs are expected to be irrelevant. The uncertainty on t_{BH} from SK is assumed to be about 1 ms. From Fig. (2), this uncertainty can be seen to change the expected number N_{del} by $\simeq 0.2$ events, which is negligible. Other possible errors, e.g., the detector background, the disregarded 0.5 ms tail of the luminosity, and ν_e and $\bar{\nu}_e$ events after t_{BH}, are even less important [8].

For a supernova that does not have the sharp cutoff in the rate characteristic of black hole formation, the model-independent $\langle t \rangle$ analysis [6] yields an m_{lim} that is *independent* of the distance D and scales as $1/M_D^{1/4}$ [6]. For the present case, m_{lim} scales as:

$$m_{lim} \sim E_c \sqrt{\frac{\langle E \rangle \, D}{\sigma_{eff} L_{BH} M_D}}\,, \qquad (6)$$

where σ_{eff} is the thermally-averaged cross section. In terms of absolute sensitivity, these techniques compare as 21 eV and 6 eV, respectively. These differences are consequences of the sharp cutoff in the neutrino flux.

Conclusions: If a black hole forms early in a core-collapse supernova, then the fluxes of the various flavors of neutrinos will be abruptly and simultaneously terminated when the neutrinospheres are enveloped by the event horizon. For a massive neutrino, the cutoff in the arrival time will be delayed by $\Delta t \sim (m/E)^2$ relative to a massless neutrino.

The Galactic core-collapse supernova rate is about 3/century or higher [8], and the work of Brown and Bethe [18] suggests that black holes are formed about half of the time. In the work of Burrows [9] and Mezzacappa and Bruenn [10], the neutrino luminosities just before black hole formation are very high. These results indicate that there is a reasonably good chance that such an event could be observed by the present and proposed supernova neutrino detectors [8]. If so, there are important practical consequences.

First, since SK can measure the neutrino energy of the $\bar{\nu}_e + p \rightarrow e^+ + n$ events, both t_{BH} and m_{ν_e} can be measured by the arrival times for different neutrino energies. An electron neutrino mass as small as 1.8 eV can be detected. *Second*, although the mu and tau neutrino energies are not measured in their neutral-current detection reactions, their masses can be measured by counting the number of events after t_{BH}. In the proposed OMNIS detector, a mu and tau neutrino mass (assumed degenerate [7]) as small as 6 eV can be detected. This is the only known direct technique with eV-scale sensitivity for these masses. *Third*, these results scale with the distance, luminosity, and detector mass as $\sqrt{D/L_{BH}M_D}$. This favorable scaling with the detector mass suggests that it would be realistic to consider even larger detectors, in order to reach 1 or 2 eV for all three neutrino masses.

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